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(54) Improving Fatigue Life of Holes

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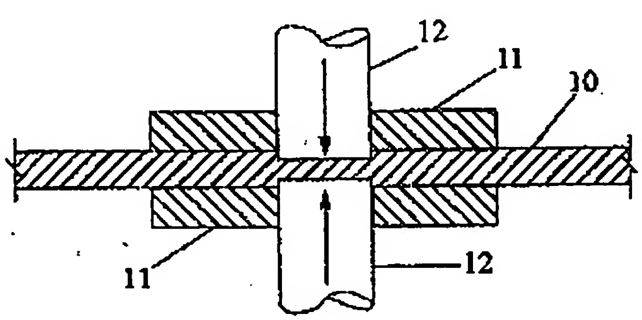

(57) Abstract

The invention relates to a method of improving the fatigue life of holes and cut-out portions formed in material sheet wherein on at least one area on the sheet where a hole is to be formed or a hole for the cut-out portion is to be formed, the sheet is compressed, and most preferably forming indentations from said compression, on at least one side, and preferably two sides of the material sheet. The process is generally applicable, but is particularly useful where the sheet is to be used in high fatigue loading and stress conditions, such as aircrafts. The invention also provides for an apparatus for improving the fatigue resistance of holes and cut-out portions in material.

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HOLE MANUFACTURE

The invention is in relation to a method of improving the fatigue life of holes and areas which are to be cut out and in particular holes and cut-out portions in structures which are subjected to fatigue loading for example aerospace and aircraft applications. The present invention also provides an apparatus for improving the fatigue life of holes and cut out areas.

In the production of aircraft, in order to fasten metal sheets together, holes are made to house the fastening means, such as rivets or bolts. However, holes are a source of localised weakness in the metal sheet or plate which can lead to failure of the particular sheet or plate due to the formation and propagation of cracks from the hole.

It is generally known that the fatigue life of a sheet or plate having a hole therethrough can be increased by generating compressive stresses within the sheet about the hole. There have been numerous ways of creating compressive stresses around a hole, one of the most common being cold-working or cold-expanding the hole using a split sleeve. In this method a hole is formed first which is large enough to receive a split tubular sleeve, but which is undersized in respect of the rivet or bolt. The split tubular sleeve which can be axially or helically split, is placed into the hole. An expansion section of the cold-working mandrel is drawn through the inside of the split tubular sleeve thus expanding the tubular sleeve and also the hole. After the expansion section of the mandrel has passed through the pre-split tubular sleeve, the tubular sleeve may be removed. The expanded tubular sleeve cannot be reused and is discarded after forming one hole. Due to the high manufacturing tolerances required for the production of such sleeves, their unit cost is high, and in cases where a large number is required (as in the case of a typical aircraft), the process becomes extremely costly to implement. Costs aside, there are further physical problems with the cold-working method. Whilst the cold-working method provides the desirable compressive stress around the hole, the compressive stress is not evenly distributed because of the split in the sleeve. The presence of the split in the sleeve also creates a sharp discontinuity on the side of the hole which itself can become a source of stress concentration. To overcome this problem, it is

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generally recommended that a suitable reaming process be applied to the hole following cold expansion. This additional procedure further adds to the production costs of such holes.

Another disadvantage of this method is that in using a tapered mandrel, a residual stress distribution which is non-symmetrical about the mid-plane of the material is created thus inducing a bending moment which, particularly in the case of thin sheets (generally less than 2.3 mm), causes local buckling of the material. Furthermore, the lack of out-of-plane constraints on the material during the expansion process often leaves a raised region at the periphery of the hole.

Another form of treatment commonly used on holes in aircraft manufacture is ring pad or stress coining. In the case of ring pad coining, a thin groove is formed which is spaced from and around an existing aperture in the structural member. U.S. 3,110,086 to Austin Phillips granted 12 November, 1963 discloses a ring pad coining method. The groove is formed by stamping, thereby cold-working the material and creating a residual compressive stress around the exterior of the hole. Although this method can enhance the fatigue life of fastener holes, several disadvantages are immediately apparent when using this process. For instance, as the grooved depression is spaced some distance from the hole, a relatively large amount of deformation is required to achieve a desirable level of residual stress. Further, for many structural members, the presence of an annular depressed ring around the hole is aesthetically, if not structurally, undesirable.

Stress coining is similar to ring pad coining, however an entire region around the hole is stamped or compressed. U.S. 3,434,327 to E. R. Speakman granted March 25, 1969 discloses a stress coining process. Stress coining relieves to a greater extent the localised stress around the hole; however, with this solution other problems arise. Generally what happens is that the impressions formed around the holes can become a stress raiser themselves, especially when the holes are fitted with rivets, bolts or the like. That is, the impressions reduce the bearing surface and thus raise the bearing stress for fastener holes. Furthermore, local indentations around the hole can create problems for members being fastened over them, particularly for thin composite

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plates; wherein the indentations can cause severe local buckling and delaminations of the plates.

Also when the stress/ring pad coining method is used to treat holes great care must be taken so that there is not excessive indentation of the area around the hole, otherwise this may result in closure of the hole or in the extreme punching out of the hole which leaves an unusable oversized hole. Excessive indentation can also lead to shear band cracking in the indented area.

Stress coining as with other prior art methods improves the fatigue resistance of the structural members but at the expense of other desirable and necessary characteristics.

The object of the present invention is to increase the fatigue life of the structural members containing holes and cut out portions but without some of the disadvantages of the prior art.

The present invention provides a method of improving the fatigue resistance of holes and cut out portions formed in material sheets for use in structure subjected to fatigue loading wherein at least one area on a sheet where a hole is to be formed or a portion is to be cut out is compressed, most preferably forming an indentation, on at least one side and, preferably both sides, of the sheet prior to the formation of the hole or the portion being cut out. Thus the compressive stress is created in the area surrounding the hole or cut out portion prior to the formation of the hole or the portion being cut out.

Advantageously, the method of the invention provides significantly improved fatigue life of holes in components. Preliminary tests illustrate at least a ten-fold increase in fatigue life of open holes. Furthermore, the method of the invention can be effectively used in relatively thin sheets since the undesirable effects of the prior art methods such as sheet buckling or peripheral deformations are significantly reduced. Similarly, by the same underlying physical principle, the fatigue life of cut out portions in which the stress critical locations have been treated by the invention will improve.

Generally the method of the invention would be useful in any application where the fatigue resistance of the structure and containing a hole or holes is to be improved.

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The method of the invention has general application in the manufacture of aircraft and aerospace equipment, where the fatigue resistance of the highly stressed structures and components thereof including the joining holes and stress critical locations, is of primary importance. Additionally, the method greatly enhances the fatigue resistance of a structure containing a hole or holes without additional weight which is most desirable in the aerospace and aircraft industries. It is also envisaged that the process will be useful in other applications such as in the manufacture of ships and other high performance (and highly stressed) vehicles and also in the manufacture of highly stressed process vessels and containers which have to withstand high pressures.

Additionally, bearing in mind the method of the present invention can be used to enhance the fatigue resistance in thin sheets containing a hole or holes, the method can be used in any high performance and lightweight applications, for example, sports equipment such as tennis and squash racquet frames and motor sport structures.

The method of the invention can be applied to any material which exhibits an elasto-plastic stress-strain relationship, that is most metals and alloys for example, those of aluminium and steel.

Preferably, the area on the sheet where the hole is to be formed is compressed from both sides by mandrels, thus most preferably forming indentations on both sides of the sheet. The mandrels may be of any cross-sectional shape, i.e. square, hexagonal, round etc. and as such, the resulting hole formed may equally be of any shape. The mandrels, apart from being flat or chamfered, may also be shaped in order to provide a countersink for the various types of fasteners.

After the area has been compressed and most preferably an indentation or indentations have resulted from the compression, the hole can be formed by any conventional method including drilling. However, the inventors have discovered that instead of drilling, one of the mandrels can be removed and the other can then be forced through to shear away the material and form the hole. Thus providing a simpler, faster method of producing a hole with improved fatigue life, by decreasing the steps required to form the hole.

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In the case of cut out portions, once the stress critical locations have been compressed and most preferably indentations have been formed by the compression, the portion is then cut out as normal.

The invention can be further understood with reference to the following illustrations of a preferred embodiment of the method of the invention.

Figure 1 : A sheet which requires a hole such that it can be fastened to another structure or sheet.

Figure 2: The same sheet as in Figure 1 with optional clamps applied to the sheet.

Figure 3: The mandrels in action around the sheet.

Figure 4: Optional step wherein one of the mandrels forms the hole.

Figure 5: The completed hole.

Figure 6 : A pretreated (dimpled) sheet with mandrels being aligned for pre-hole compression.

Figure 7 : A pretreated (pilot hole) sheet with mandrels being aligned for pre-hole compression.

Figure 8 : An oversized hole compared to the indentations / mandrel size.

Figure 9 : An undersized hole compared to the indentations / mandrel size.

Figure 10: Indented area to be cut out.

Figure 11: Cut out area.

Figure 12 : A graph of the first set of comparative results between drilling, prior art cold working and the present invention.

Figure 13: A graph of another set of comparative results between drilling, prior art cold working and the present invention.

Figure 14: An illustration of the specimen used in the comparative examples of Figure 13.

Figure 15 : A graph showing fatigue results similar to Figure 13; with the additional comparison of no-hole.

Figure 16: A graph comparing one-sided indentation compared to two-sided indentation prior to hole formation."

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Figure 17: Illustrates a front view and side view of a specimen wherein three layers of material with holes made by drilling, the prior art cold working or the invention, are riveted together.

Figure 18: A graph of a set of comparative results wherein the holes are produced by drilling, prior art cold working or the present invention then riveted together.

With reference to Figures 1 to 5, sheet 10 which requires a hole 20 to be formed therein is clamped by clamps 11 in the vicinity of where the hole is to be made. The holes 13 provided in clamps 11, outline the portion of the sheet 10, where the hole 20 is to be formed. In Figure 3, mandrels 12 which are guided by clamps 11 commence their compression and indentation on sheet 10. The top mandrel acting downwardly and the bottom mandrel acting upwardly in the direction of the arrows. It has been discovered that the degree of fatigue life improvement generally increases with an increase in indentation depth. Whilst this could also be true for the prior art methods, excessive indentation for the coining techniques, as previously stated, can lead to hole closure or even complete punch-out.

The mandrels 12 may then be removed and the hole 20 is formed by conventional methods such as drilling and the like. Alternatively, as is illustrated in Figure 4, only one of the mandrels 12 is removed and the other remaining mandrel stamps out the reduced section 14 to form the hole 20.

Although the use of the restraining means or clamps 11 is not an essential part of the process, the use thereof further enhances the fatigue life by virtue of restricting any out-of-plane deformations thereby creating a greater region of residual stress than otherwise possible. In addition, this restraining procedure results in the structure containing the hole or holes being relatively free from the distortions which are an undesirable by-product of the prior art cold expansion methods.

Alternatively, where only pre-hole indentation is required on one side, two sheets (not shown) can be processed simultaneously, wherein as is illustrated in Figures 1-5, instead of item 10 being one sheet, item 10 is two separate sheets (not shown). Mandrels 12 can then compress and most preferably form

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indentations on the two sheets simultaneously on a single side. Similarly, the mandrels 12 would be able to shear away the material (from both sheets) to form the holes in each sheet.

Figure 6 illustrates a sheet 10 which requires a hole 20 to be formed.

In order to ensure that the indentations are formed in the correct hole area, the sheet is preferably provided with location means (15,16). In Figure 6 the location means 15 is in the form of a dimple. Figure 6 illustrates pre-hole indentation from only one side occurs prior to forming the hole. The dimple 15 cooperates with protrusion 17 on the mandrel 12. The provision of the location means 15 and cooperating protrusion 17 on the mandrel 12 assists in ensuring that the indentation is correctly positioned and that the hole area has been pretreated as required. Figure 7 illustrates another form of location means 16 which is in the form of a pilot hole. Figure 7 illustrates pre-hole indentation from both sides of the sheet 10. It must be noted that the pilot hole is just a location means to cooperate with and to assist in the centring of the mandrels and is not the actual fastening hole. Thus, the pilot hole 16 (as do the dimples 15) assists in ensuring that the indentations are in the correct hole area and in the case of double-sided indentations, the indentations formed on both sides are correctly aligned.

Whilst it is envisaged that the drill or punch size in order to form the hole would generally be the same size as the indentations formed, improved fatigue resistant results are also observed wherein the indentation is smaller or larger than the final hole size. Reference is now made to Figure 8 wherein the final hole 20 is larger than the indentations (shown in dotted lines). In this case the hole will be formed by drilling or by using a larger punch / mandrel than the indenting mandrels. Figure 9 illustrates the situation wherein the final hole 20 is smaller than the indentations 18. Similarly, the hole is formed by drilling or by using a smaller punch / mandrel than the indenting mandrels. Additionally, whilst Figures 6 to 9 do not illustrate this feature, it is generally preferred that the sheet 10 be retained in position, by clamps or the like during the indentation and punching / drilling steps as was shown in Figures 2 to 4.

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Figures 10 and 11 illustrate the application of the present invention to areas which are to be cut out. Figure 10 illustrates sheet 110 wherein area 120 is to be cut out. Prior to the cutting out process, stress-critical locations of the area to be cut out are indented 121 in a similar manner as described and discussed in Figures 1 to 9 above. Once the indentation process is complete, the area is cut out using conventional techniques resulting in the cut out area 120 as illustrated in Figure 11.

Tests have been conducted based upon the process of the present invention.

The results of the tests are shown in Figures 12 and 13. The results shown in Figure 12 were preliminary tests comparing the three processes, that is, drilled, cold-worked and the process of the present invention. All of the samples were the same, being dog-boned shaped specimens made from Aluminium 2024. The dog-bone specimen used in these tests, (the results of which are illustrated in Figure 12) were substantially square in shape, wherein the specimen resembled a capital "I". The hole was formed in the narrow portion of the dog-bone. The cross-section in the relevant hole area of the samples was 41.5 mm x 1.6 mm. Each of the holes formed were 4 mm in diameter. The prior art "drilled" method involved drilling the hole in the sample to 4 mm. The 4 mm holes formed in the prior art "cold expanded" specimens were made using the Fatigue Technology Inc. (FTI) cold expansion process.

The specimens made by the present invention were compressed and indented by two mandrels (4 mm in diameter), each with a 25 kN load applied thereto, positioned on either side of the samples and guided by clamps which were holding the samples. The hole was punched using one of the mandrels. It should be noted that the indentation depths (and loading) vary with the type of material and hole size.

Tests were performed on a 50 kN capacity servo-hydraulic testing machine with the following loading conditions :

Frequency of loading = 20 Hz
Ratio of maximum / minimum load = 10.

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Each of the samples were cyclically stressed until failure of the specimen occurred. The results of the preliminary trials are illustrated in Figure 12.

Stress shown on the graph is obtained by :

$$\text{STRESS} = \frac{\text{MAX LOAD - MIN LOAD}}{\text{CROSS-SECTIONAL AREA}}$$

It should be noted that for the "drilled" and "cold expanded" specimens the specimen failed from the hole.

The specimens produced by the method of the present invention began failing at the specimen edges (at the top and bottom portions of the dog-bone) and not the hole. Thus, the true lives of the holes produced by the method of the present invention is assumed to be higher than shown. On reviewing Figure 12, it can be seen that specimens produced by the present invention could withstand over double the number of cycles for a particular stress than the "cold expanded" holes and over ten times the number of cycles that a drilled hole could withstand.

Further comparative tests have been conducted comparing the "drilled" process, "cold expanded" process and the process of the present invention using a different shaped sample to the previous preliminary tests. Figure 14 illustrates the sample used in the further tests. The sample made of Aluminium 2024 had dimensions 175 x 60 x 1.6 mm wherein an arc of radius 85 mm was removed from each of the long sides of the sample, resulting in a smooth dog-bone shaped specimen. The narrowest portion of the dog-bone was 45 mm. The 4 mm hole was formed and centred at the narrowest portion. The "drilled" and "cold expanded" specimens were made using the same processes as in the preliminary tests. The specimens made by the present invention were compressed and indented by two mandrels (4 mm) each with a 16 kN load applied thereto, positioned on either side of the samples and guided by clamps which were holding the samples.

These tests were performed on the same 50 kN capacity servo-hydraulic testing machine with the same loading conditions as with the previous preliminary tests.

Once again, each of the samples were cyclically stressed until failure of the specimen occurred. The results of the tests are illustrated in Figure 13.

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As with the preliminary tests the "drilled" and "cold-expanded" specimens failed from the hole.

Similarly, the specimens produced by the present invention failed at the specimen edges. However, where in the preliminary tests the specimens failed near the fixed end portions, the specimens of the subsequent tests failed closer to the neck or narrowest portion of sample.

It can be observed from Figure 13, that the specimens prepared by the present invention outlived the specimens prepared by the other two methods under the loading conditions considered.

For stress levels of 140 MPa to 200 MPa, the samples of the present invention outlived the FTI specimens by approximately from $2^1/_2$ to $1^1/_2$ times respectively. The improvement in fatigue life is even greater below 140 MPa.

Figure 15 illustrates the same results as in Figure 13; however, with the additional control data of fatigue loading metal samples with no holes, the specimens were the same as the samples with holes formed therein, but without holes formed therein. It can be noted with reference to Figure 15, that the specimens prepared with holes of the present invention perform equally as well, if not in some cases better, than the "no-hole" specimens. A likely explanation for this result is that the method of the invention provides compressive residual stresses at the resulting hole perimeter which are so effective in preventing fatigue such that the critical or most likely failure site of the specimen is shifted from the hole edge to the outer edge of the specimen. Thus, for a given applied set section stress, the dynamic stress at the outer edge of a specimen without a hole is slightly higher than that of a specimen with a hole produced by the method of the present invention. Similarly, there is a real potential for a component containing a hole or holes produced by the method of the present invention to out perform an otherwise identical component which does not contain a hole at all.

Essentially the process of the present invention introduces sufficient and effective compressive residual stresses such that the critical or most likely failure site is shifted from the hole edge to the outer specimen edge.

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Figure 16 illustrates tests conducted using the present invention comprising one-sided indentation with two-sided indentation prior to formation of the hole. It is observed that one-sided indentation can provide as good a result as indenting from both sides without requiring a significant increase in load. In particular, it can be seen from Figure 16 specimens produced with a one-sided indentation of 18 kN, which represents only a 12.5% increase in indentation force, showed a comparable fatigue resistance to that obtained by the two-sided indentation process.

Figure 18 shows the results of tests comparing samples which had holes produced in each of three metal sheets by drilling, cold-working and the process of the present invention, and then joining the three sheets in a manner shown in Figure 17, which illustrates Sample 30, with rivets in sheets 31.

More specifically, the specimens of the tests were constructed from three sheets of 60 mm wide x 1.6 mm thick, aluminium 2024 sheets. Two 4 mm diameter aircraft grade countersunk rivets spaced at 25 mm were used to fasten the sheets 32 together as shown in Figure 17.

The three types of holes were made as follows:

(i) Drilled: Holes were drilled such that a snug push fit with the rivets was obtained.

(ii) FTI: Holes were made using the Fatigue Technology Inc cold expansion process as discussed previously. The maximum allowable cold-working by this method was obtained - 5% expansion of initial hole.

(iii) The invention: - compression and indentation was made from both sides of the hole with an indenting force of 18 kN, prior to the formation of the hole.

The same loading conditions as used above in previous tests were applied to the riveted joint specimens. The results of the tests are illustrated in Figure 18. Stress shown on Figure 18, is the average fastener stress which is as follows:

$$\text{Average fastener stress} = \frac{\text{LOAD}}{4 \times \text{cross-sectional area of a single rivet}}$$

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By comparing the results of Figure 18, with those of Figure 13, it can be seen that the results of Figure 18 show a greater degree of scatter compared to the open hole results. This is not entirely unexpected because of the method of manufacture of the specimens which involves the additional process of manually fixing rivets, which itself is subject to variations.

However, it is clear from reviewing the results shown in Figure 18, that the specimens treated with the process of the present invention, out perform specimens treated by the prior art cold expanded method and the drilled method only.

By way of example, for shear stress of 140 MPa. the expected fatigue lives for the drilled holes, cold-expanded holes and the holes manufactured using the present method of the invention were approximately 200,000, 400,000 and 2,000,000 respectively. In this particular example, the cold-expanded process and the process of the present invention showed a two-fold and ten-fold, respectively, improvement over the drilled only hole.

The present invention also provides an apparatus for improving the fatigue resistance of holes and cut out portions in material sheets comprising a means for compressing and indenting at least one side of the sheet, preferably both sides. The apparatus may also comprise restraining means or clamps to retain the sheet in position. Mandrels are preferably used to compress and indent the sheet. Furthermore, one or both of the mandrels may be capable of stamping out the hole after indentation.

It is generally considered that the present invention is a preventative manufacturing method which can be used when manufacturing structures which are prone to fatigue failures such as aircraft and other high performance and highly stressed components.

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THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A method of improving the fatigue resistance of holes and cut-out portions formed in material sheets for use in structures subjected to fatigue loading wherein at least one area on a sheet where a hole is to be formed or a hole for the cut-out portion is to be formed is compressed on at least one side prior to the formation of the hole.

2. The method of Claim 1, wherein the sheet is compressed on both sides of the sheet.

3. The method of Claims 1 or 2, wherein an indentation is formed as a result of the compression.

4. The method of Claim 3, wherein the cross-section of the indentation has the same size cross-section as the hole to be made.

5. The method of any one of Claims 1 to 4, wherein a means for compressing is utilised to compress the sheet and also form the hole to be made.

6. The method of any one of Claims 1 to 5, wherein the sheet is constrained in a restraining means.

7. A sheet comprising at least one hole manufactured by the method as defined in any one of claims 1 to 6.

8. A component comprising at least one hole manufactured by the method as defined in any one of claims 1 to 6.

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9. An apparatus of improving the fatigue resistance of holes and cut-out portions in material sheets for use in structures subjected to fatigue loading comprising a means for compressing at least one side of a sheet in an area where a hole is to be formed or a hole for the cut-out portion is to be formed prior to the formation of the hole.

10. The apparatus of claim 9 wherein the means for compressing can also indent the sheet.

11. The apparatus of claims 9 or 10 wherein the means for compressing is also for forming the hole.

12. The apparatus of any one of claims 9 to 11 wherein the means for compressing, compresses both sides of the sheet.

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Fig 1.

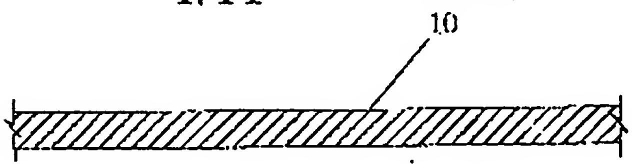

Fig 2.

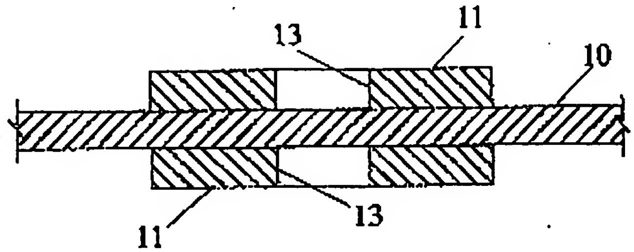

Fig 3.

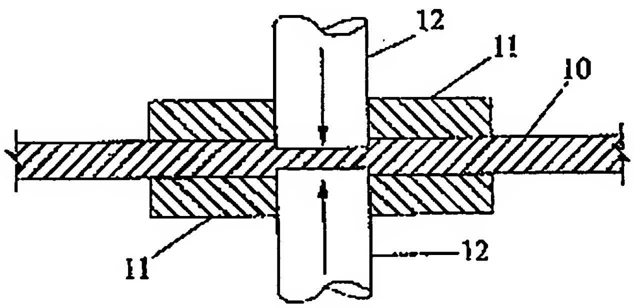

Fig 4.

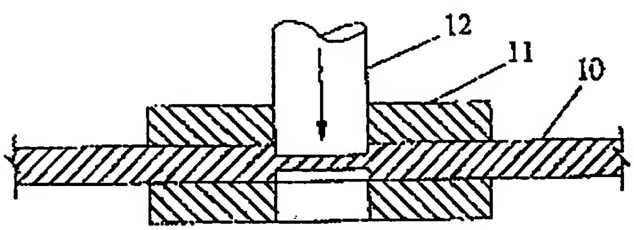

Fig 5.

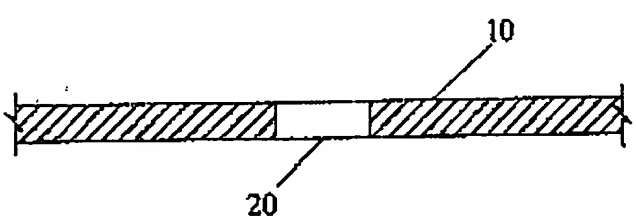

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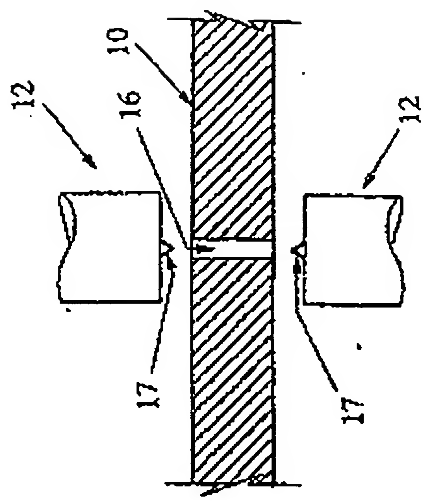
Fig 7.



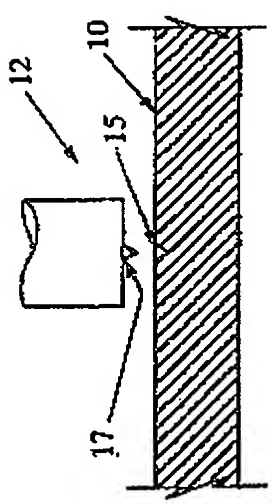


Fig 6.

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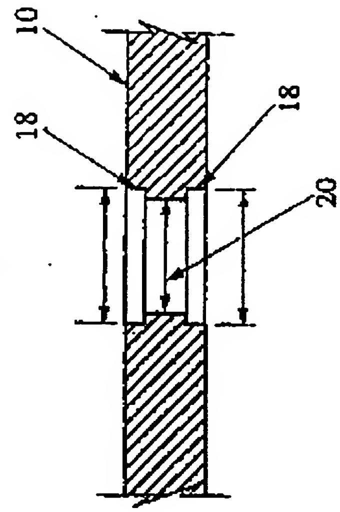

Fig 9.

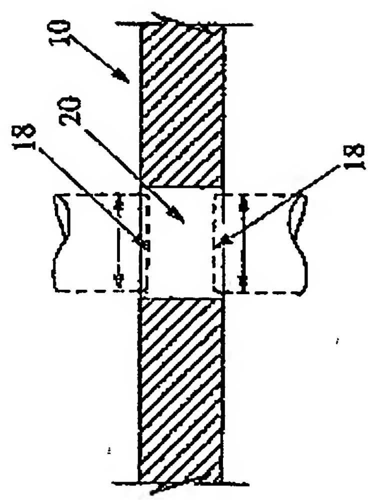

Fig 8.

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Fig 10.

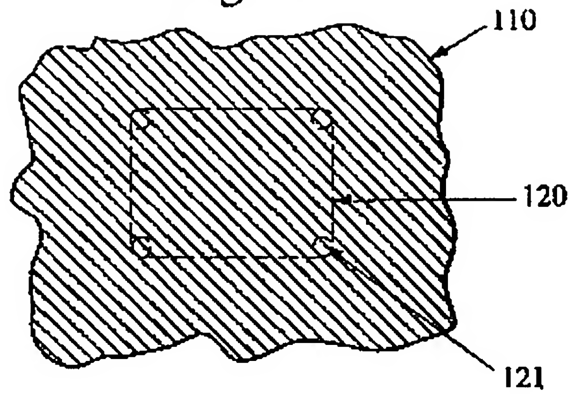

Fig 11.

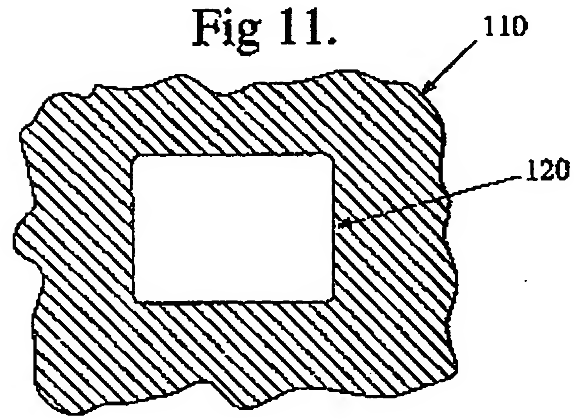

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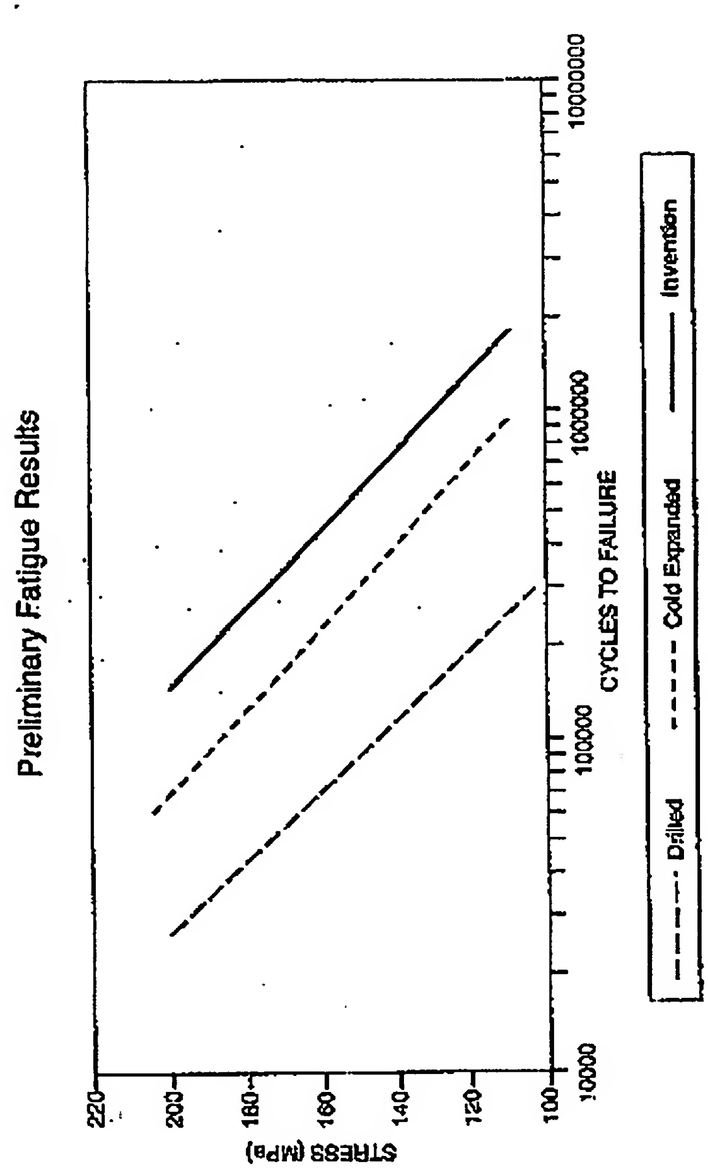
Fig. 12.



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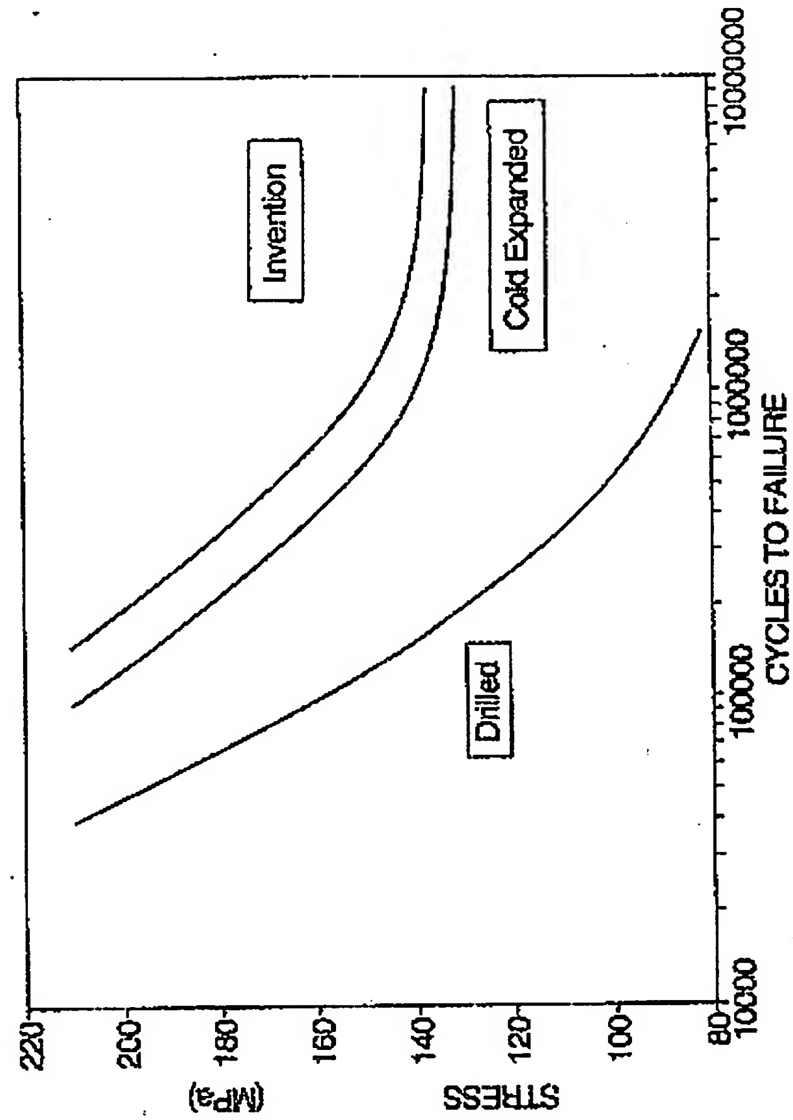

Fig 13.

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Fig 14.

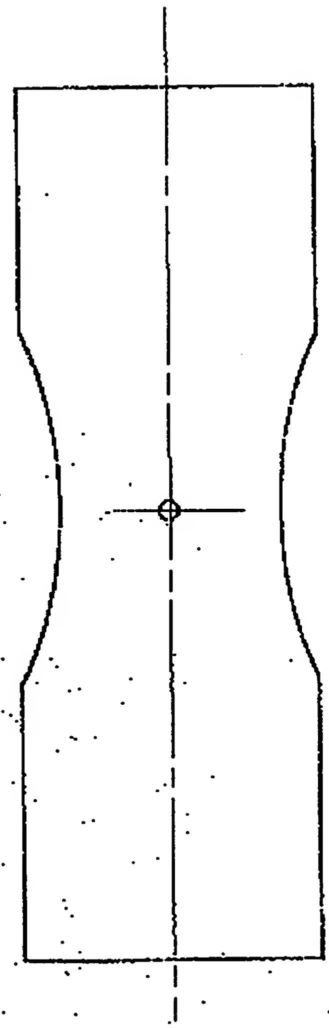

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Fig 15.

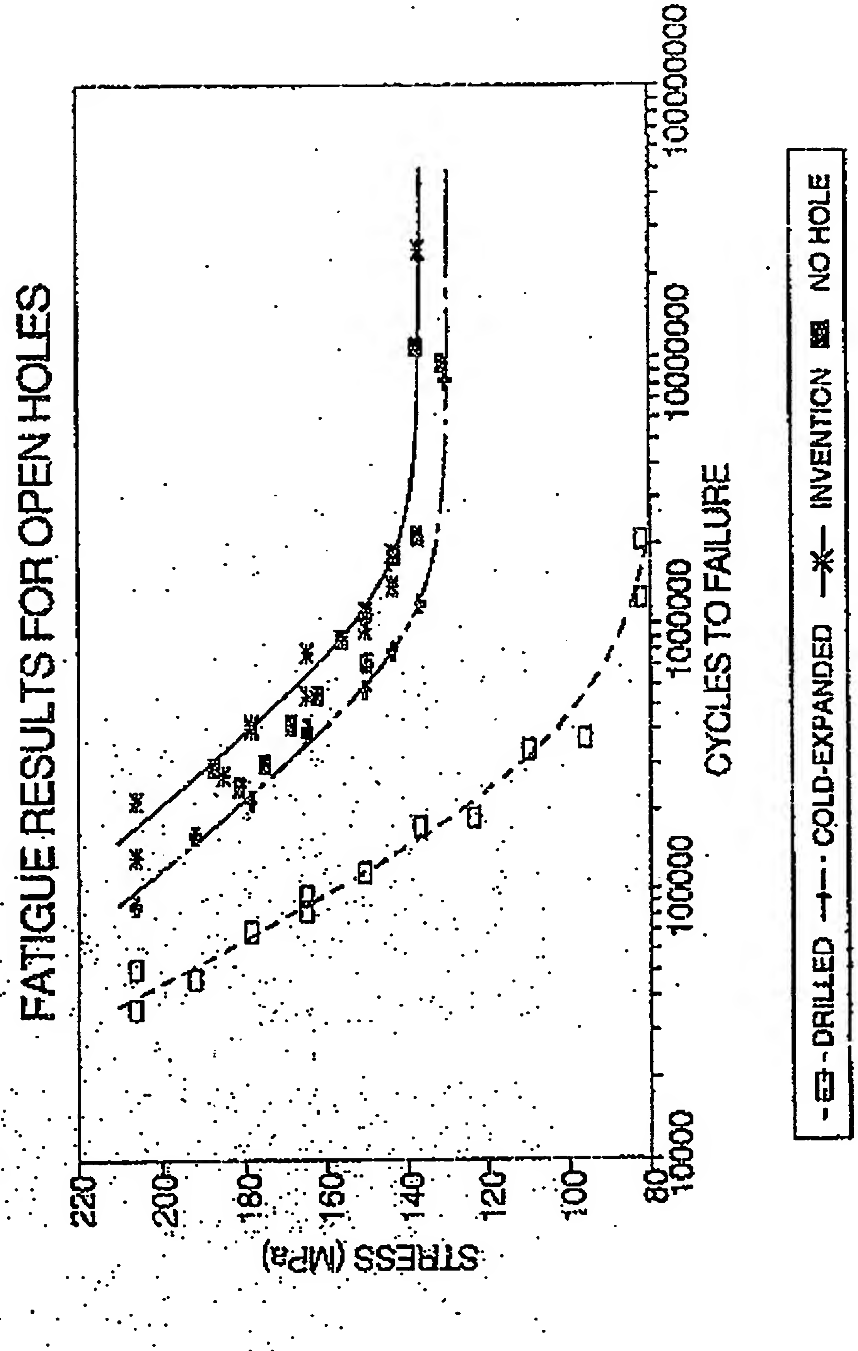

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Fig 16.

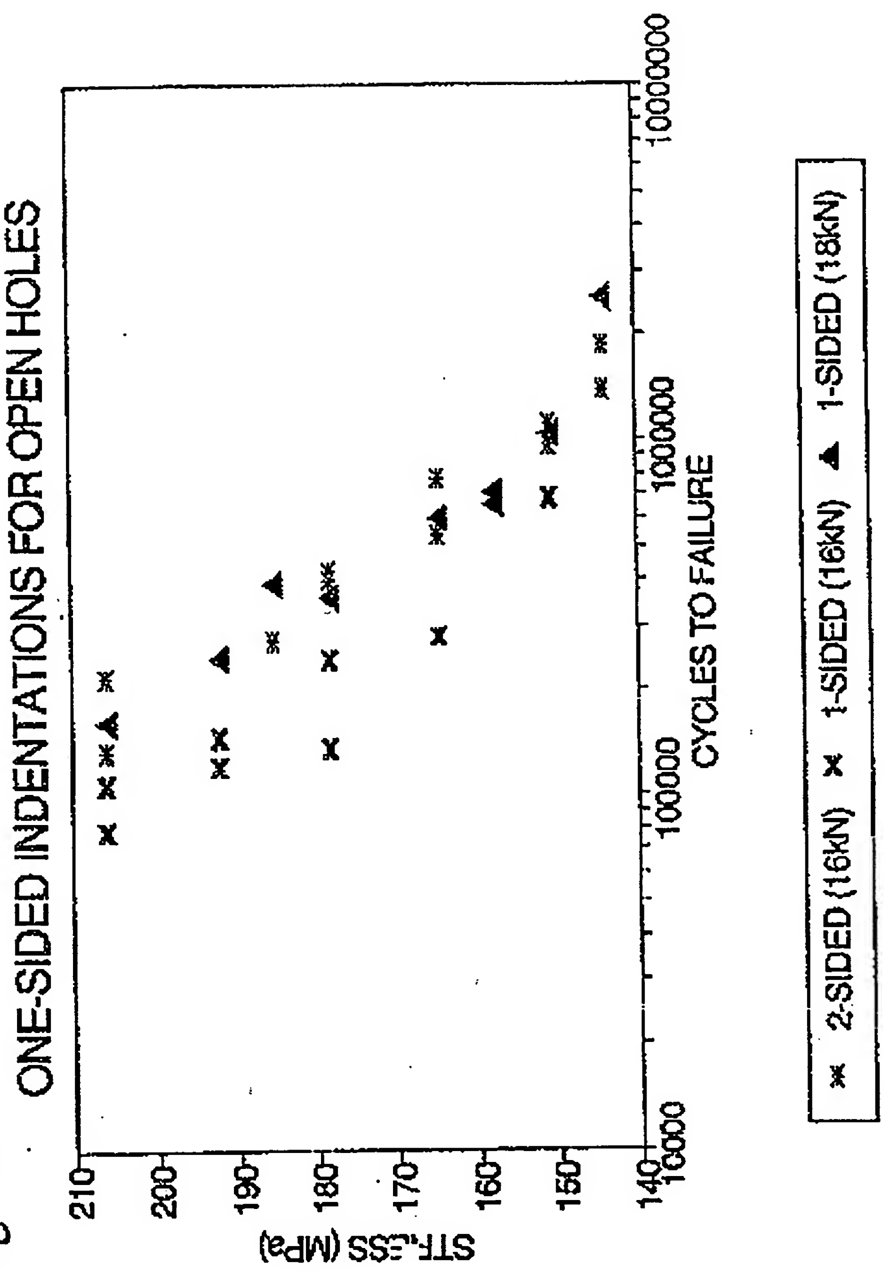

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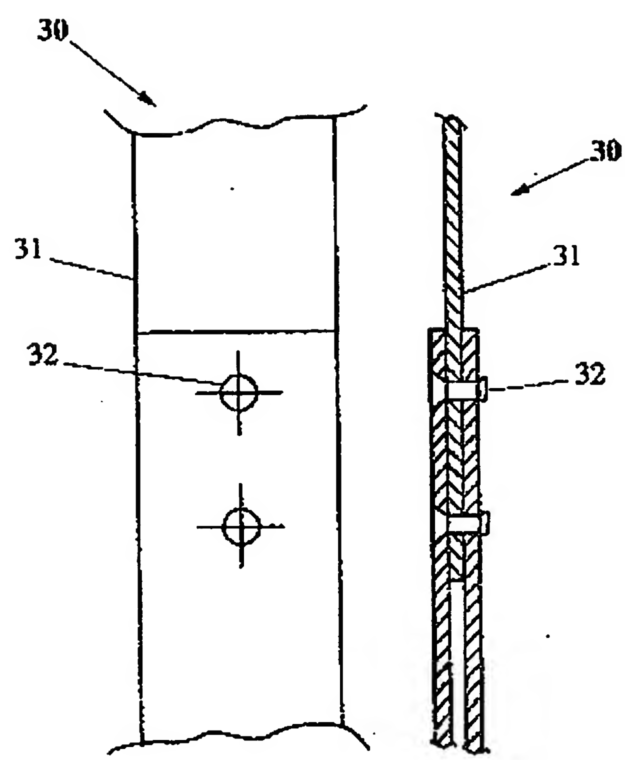
Fig 17.



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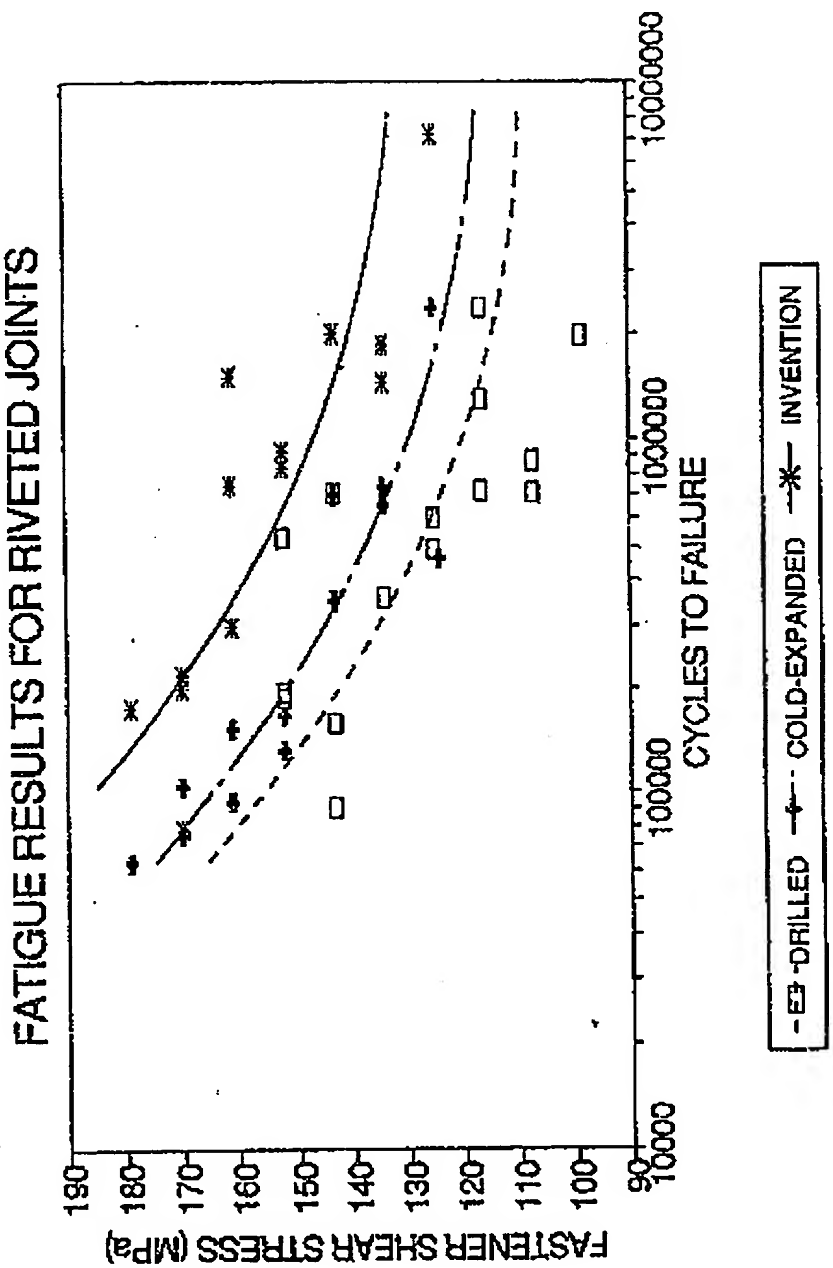

Fig 18

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